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THE LASER INTERFEROMETER SPACE ANTENNA MISSION

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*Abstract**

The Laser Interferometer Space Antenna (LISA) mission is designed to detect and study low-frequency gravitational radiation. The types of astrophysical sources which will be observed include galactic binary star systems composed of a compact star and a massive black hole, galactic neutron star-black hole binaries, and signals from the coalescence of supermassive black holes, found at the centers of most galaxies, during mergers of galaxies. Gravitational waves can be observed by measuring the changes in distance they cause between freely floating objects in space. LISA will consist of three spacecraft in orbit around the sun; the orbits are carefully chosen so that the distance between any two spacecraft is approximately 5 million km. The distance changes between spacecraft will be measured with picometer accuracy using laser interferometry. There are several technology challenges to implementing the LISA mission, which include high performance 'drag-free' control and high precision laser interferometry. LISA will be implemented by a partnership between the National Aeronautics and Space Administration and the European Space Agency. LISA is a key element in the Structure and Evolution of the Universe theme within NASA's Office of Space Science, and is also a Cornerstone mission in ESA's Horizons 2000 program.

Introduction

The goal of LISA (Laser Interferometer Space Antenna) is to detect and study low-frequency astrophysical gravitational radiation. Gravitational waves are generated by a time-changing mass quadrupole, such as a binary star system (Figure 1). LISA will have enough sensitivity to detect the gravitational radiation from regions of the universe which are strongly relativistic, e.g. in the vicinity of black holes. Such regions are difficult to study by conventional astronomy. LISA will also be sensitive enough to measure gravitational waves from several thousand binary star systems in the Milky Way galaxy. A few such sources have already be identified from optical astronomy. These systems will appear as signals with periods ranging from a few minutes to a few hours with nearly constant amplitude. Measuring the phase of the signals as the LISA constellation revolves about the sun will allow a determination of the direction to the sources.

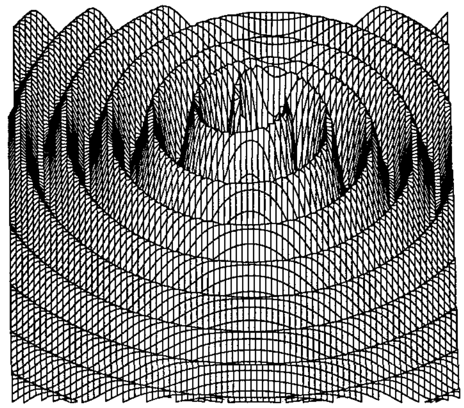

Figure 1. An illustration of the gravitational waves generated by a binary star system

Gravitational waves are propagating gravitational fields, "ripples" in the curvature of space-time which cause a strain distortion of space; the apparent distance between points in space changes by an amount proportional to the distance between the points times the (dimensionless) amplitude of the gravitational wave. LISA will detect these strains down to a level of a few parts in 10^{-23} in one year of observation time by measuring the fluctuations in separation between freely-floating test masses separated by 5×10^6 km. The distance changes will be measured by laser interferometry, which determines the distance between the test masses with an accuracy of a small fraction of the laser wavelength.

The three LISA spacecraft will be in individual orbit about the sun (Figure 2). They will form a triangle with sides 5×10^6 km long. The spacecraft orbits will be chosen such that the separation between spacecraft will be nearly constant throughout the year even though each spacecraft is in its own orbit [1]. The center of the triangle will be in the ecliptic plane 1 AU (150×10^6 km) from the Sun and 20° (52×10^6 km) behind the Earth. The triangle will have an apparent rotation about the center of the formation once per year due to the individual spacecraft orbits. The spacecraft positions with respect to each other will not be actively adjusted at any time after initial spacecraft deployment.

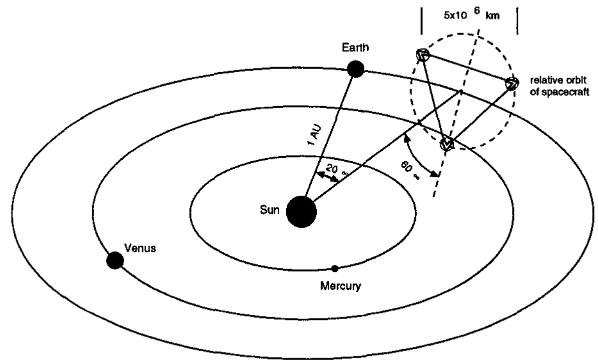

Figure 2. Schematic diagram of the LISA configuration. The three spacecraft will form an equilateral triangle with sides 5 million km long. The plane of the triangle will be tilted 60° out of the ecliptic. The drawing is not to scale.

Each spacecraft will contain two freely-floating test masses. The test masses will be shielded from extraneous disturbances (e.g. solar pressure) by the spacecraft. To keep the solar radiation pressure from pushing the spacecraft into contact with the test masses, the distance between the test masses and the spacecraft will be measured (capacitively) and thrusters fired to counteract the solar radiation pressure. This control is similar to the 'drag-free' control used to counteract atmospheric drag in some Earth-orbiting satellites.

The three spacecraft will be used to form a giant Michelson interferometer. The interferometer will be formed using laser signals transmitted between spacecraft. Each spacecraft will contain a payload including two test masses, two 1 W lasers, and two 30 cm diameter telescopes for the transmission and reception of laser signals. One spacecraft will be designated the central spacecraft. The lasers in the central spacecraft will be phase-locked together, so they effectively behave as a single laser. The central spacecraft will transmit a continuous laser beam to the two other spacecraft. The lasers in the end spacecraft will be phase-locked to the incoming light, and thus act as amplifying mirrors. The returned beams at the central spacecraft will mixed with the transmitted light on a photo-diode. The phase shifts of the resulting signals will then be measured. The phase measurements of the two interferometer arms will be differenced to determine changes in distance between one pair of spacecraft versus the other pair. This differencing is necessary to cancel out frequency instability of the central lasers, which would otherwise mask the signal due to gravitational waves. The resulting distance accuracy will be about one picometer.

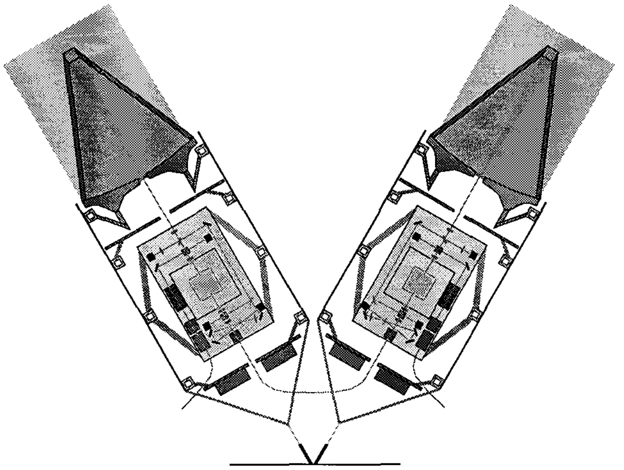

Figure 3. Cross section of the two optical assemblies comprising the main part of the payload on each LISA spacecraft. The two assemblies will be mounted from flexures at the back (bottom of figure) and from pointing actuators (not shown) at the front, near the primary mirrors.

Because of the symmetry of the LISA spacecraft design, any of the three spacecraft can act as the central spacecraft of the Michelson interferometer. This allows for redundancy in the case of a partial payload failure. If all payload items are properly functioning, then it will be possible to have signals propagating between each pair of spacecraft and have two linearly-independent Michelson interferometers in action simultaneously. This allows for measurement of both of the two possible polarizations of gravitational waves and gives improved sensitivity.

The sensitivity of LISA to gravitational waves is shown in Figure 4. At the lowest frequencies the LISA sensitivity will be limited by displacement of the test masses by noise forces such as fluctuations in the solar radiation pressure. For frequencies above 2×10^{-3} Hz the sensitivity will be limited by noise in the interferometer measurements, including the laser shot noise. For frequencies above 3×10^{-2} Hz the sensitivity will be reduced because at the higher frequencies the wavelength of the gravitational radiation is shorter than the distance between test masses. The interferometer noise limit is based on the assumption of 1 W laser and 30 cm diameter telescopes for transmission and reception of laser signal between the test masses. The test-mass noise is based on models of expected noise forces. The low-frequency sensitivity based on noise forces can be reduced by increasing the distance between test masses, at the cost of reduced sensitivity at the higher frequencies. The choice of 5×10^{6} km for the separation between test masses has been made as a compromise between increased science return at low frequencies and cost and technical issues associated with larger separations.

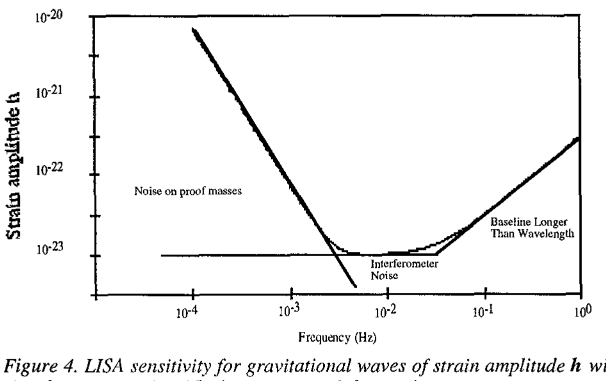

*Figure 4. LISA sensitivity for gravitational waves of strain amplitude **h** with signal-to-noise ratio of 5 after one year of observation.*

<u>LISA versus ground-based gravitational-wave detectors</u>

Several ground-based laser interferometers with arm lengths of several kilometers are now under construction. These km-size ground-based laser interferometers will be sensitive to gravitational waves at frequencies from ~10 Hz to ~1000 Hz. Ground-based detectors are expected to provide fundamental information about coalescing binary stars, the core collapse of supernovae events, and the distribution and properties of pulsars. However, ground-based detectors will always be limited to frequencies above 1 Hz due to the background of Newtonian gravity variations on the Earth which are indistinguishable from gravitational waves.

LISA will complement the next-generation ground-based detectors by opening the low-frequency window to the universe for gravitational waves, where low-frequency refers to the frequency range 0.1 mHz to 1 Hz. This frequency range contains the only sources of gravitational waves that are both theoretically well-understood and known to exist in our neighborhood; the galactic neutron star binaries. The low-frequency gravitational radiation spectrum also contains the astrophysically most interesting sources. Only in the low-frequency range can the emission from massive black holes in the interior of galactic nuclei be observed.

Figure 5 shows a comparison of the LISA and ground-based detector sensitivities. LISA will observe at frequencies approximately one million times lower (or wavelengths one million times longer) than ground-based detectors. This large difference is similar to the difference in wavelength for the visible and x-ray portions of the electromagnetic observation spectrum. Both spectral regions give a different view of the physics of the universe.

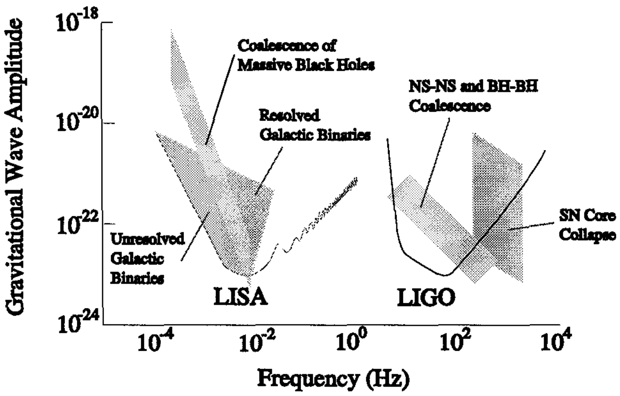

Figure 5. The gravitational spectrum for LISA and ground-based observatories.

<u>Technology Challenges</u>

The LISA science objectives lead to the measurement requirements, which are to determine the changes of distance between test masses separated by 5×10^{6} km with picometer precision over a frequency range of 10^{-4} Hz to 10^{-1} Hz. The technology challenges are thus the development of a system to measure changes in distances between test masses, and of isolating the test masses from external disturbances so that changes in their separation due to gravitational waves are not masked by motions due to other forces. The technology developments needed are divided in to the three areas of inertial sensors, micronewton thrusters, and picometer interferometry.

The major LISA technology challenge is the need for test masses sufficiently isolated from non-gravitational forces. The desire to measure distance changes, due to gravitational waves, of order 10 pm, for frequencies from 10^{-4} Hz to 10^{-1} Hz, means that the non-gravitational forces on the test masses need to produce accelerations less than 3×10^{-15} m/s^2/$\sqrt{\text{Hz}}$ or $< 3\times10^{-16}$ g. LISA depends on the design of an *inertial sensor* which will provide a freely floating test mass with sufficently low distrubances.

Some of the noise forces on the test mass are caused by fluctuations in the distance between the test mass and the rest of the spacecraft. For example, the spacecraft mass has a gravitational pull on the test mass and thus fluctuations in the position of the spacecraft cause fluctuations in the force on the test mass. Because of this the position of the spacecraft must be controlled to stay centered on the test mass. The position control requirements, derived from the inertial sensor requirements, in turn place requirements on the spacecraft thrusters. With the current mission design, the thrusters are required to have a thrust noise of about 10^{-7} N, with a continuous thrust of about 25 μN in order to oppose the force from solar radiation pressure. A new class of *micronewton thrusters* is needed to meet these requirements.

Measurement of changes of distances between test masses is routinely done with laser interferometry. For ground-based gravitational wave detectors, techniques for measuring distance changes of order 10^{-19} m have been developed and demonstrated over the past 20 years. However, interferometers for ground-based gravitational-wave detection have been optimized for motions at much higher frequencies than desired for LISA, and at much higher laser signal powers. There are a number of error sources associated with the low-frequency *picometer interferometry* to be used for the LISA distance measurements which much be addressed.

Inertial Sensors

Each LISA spacecraft will carry two inertial sensors. The inertial sensors consist of a freely falling test mass, an enclosing housing with capacitor plates for sensing and forcing, a discharging subsystem, a caging mechanism, a venting mechanism and associated electronics.

The inertial sensor will serve three interrelated functions. The design of the inertial sensor will limit unwanted disturbances from stray forces on the test mass to an acceptable level (i.e., less than that caused by gravitational waves between 0.0001 and 0.003 Hz). And, the inertial sensor will provide attitude and displacement information to the spacecraft for drag-free control.

As the defining end mirror of an interferometer arm, each test mass of an inertial sensor must have an acceleration noise less than $3x10^{-15}$ $m/s^2/\sqrt{Hz}$ in the range of 0.0001 Hz to 0.003 Hz. For purposes of drag-free control, the inertial sensor must sense the position of the test mass with respect to its housing with a resolution of 10^{-9} $m/\sqrt{Hz}$ and the orientation with a resolution of $5x10^{-8}$ radian/$\sqrt{Hz}$.

The LISA inertial sensor development is constrained by the fact that the desired performance cannot be demonstrated on the ground. Similar devices have been developed and tested on the ground at the level of 10^{-9} $m/s^2/\sqrt{Hz}$, which is the practical limit to which the acceleration of $10m/s^2$ from the Earth's gravity can be removed by keeping one axis of the sensor orthogonal to the local gravity vector.

Some space testing of inertial sensors has been done, and several missions are planned, with launches in the 2000-2002 time frame, that will employ sensors analogous to the LISA inertial sensors. These include Gravity-Probe B, whose gyroscope assembly will be also used as an inertial sensor for drag-free spacecraft control, and the CHAMP and GRACE missions which will employ accelerometers developed by ONERA to measure the atmospheric drag force.

From experience developed from building these devices, and from specific tests done to measure each possible noise source, it is possible to design an inertial sensor that will meet the LISA requirements. The types of noise forces that can affect the inertial sensor test mass can be identified and separately characterized in laboratory tests. Based on the noise models and tests, detailed instrument designs for inertial sensors meeting the LISA requirements have been completed [2]. However this sensor cannot be operated, much less tested, in the Earth's gravity, making this a high-risk technology.

It is thus highly desirable to perform a flight demonstration of candidate inertial sensors. Such a test would consist of two inertial sensors, each with a test mass with its own housing and electronics, on a single spacecraft. The performance would be validated by using one for spacecraft drag-free control, and measuring the position of the second with respect to the first to show that both are following the same trajectory, under the influence of gravitational forces only. Any non-gravitational force would appear as a change in the position of one test mass with respect to the other.

Micronewton Thrusters

LISA requires thrusters with the capability of balancing the solar radiation pressure, with its small variations, with low enough noise such that the spacecraft can be kept centered on one of the instrument test masses to the required accuracy (~10 nm/$\sqrt{Hz}$). The thrusters must also provide very fine spacecraft pointing control. This gives rise to the thruster requirements for thrust controllable in the range 5 μN to 25 μN with noise less than 0.1 μN/$\sqrt{Hz}$.

The best candidates for meeting these requirements are small ion thrusters which have been developed, partly under funding by ESA, for satellite station keeping and for satellite charge control. These devices operate by ionizing and accelerating atoms from a liquid-metal reservoir. These Field-Emission Electric Propulsion (FEEP) thrusters provide thrust in the desired range, with very high efficiency, allowing a very small amount of propellant to last for more than the 3 year LISA prime science mission.

The thrust, and the thrust noise, of these thrusters has so far not been directly measured. Instead the thrust characteristics have been derived by measurements of the ion current and applied voltage to compute the applied thrust. There are possibly errors in this computation if there are ejecta other than single ionized atoms (i.e. droplets). The thrust is difficult to measure directly because it is so small. However work is underway in Europe to develop torsion balance experiments to directly measure the thrust.

The lifetime issues arise from the high voltages used to ionize and accelerate the atoms to high velocity. There can be erosion of the accelerating grids and ejecting tips. Also the ion stream needs to be combined with an ejected stream of electrons to keep the spacecraft electrically neutral. The device to do this, the neutralizer, had been subject to lifetime limiting effects for larger ion engines and may be a factor here as well.

Picometer Interferometry

Successful execution of the LISA mission relies on the ability to measure changes in the separation between test masses to < 10 pm/$\sqrt{Hz}$, down to 10^{-4} Hz. For obvious practical reasons, much of the technology development and validation for LISA will be carried out on the ground, in an environment that is significantly different from the one in which the instrument will be required to perform. Therefore, LISA interferometry development will rely heavily on emulating in-orbit conditions in a laboratory environment. The common paradigm is to use a succession of test beds. While no single test bed can fully simulate the space environment, the overall test program ensures that all critical aspects are covered.

The ground-based laboratory environment makes testing difficult mainly because:

- the presence of air limits the interferometric resolution to ~1 nm, for an optical path of a few meters. A similar limitation applies to laser-gyro measurements, because of airflow along the optical path, which causes non-reciprocal phase shifts.
- typical vibration levels are a few micrometers at a quiet location, with most of the energy concentrated at and around the so called micro-seismic peak, at approximately 0.1 Hz. Practical vibration isolation systems can attenuate vibration transmitted from the ground above ~1 Hz.
- temperature variations in a typical lab are of the order of 0.1^{o}-1^{o} per hour, while LISA-grade performance requires much better thermal stability over several hours.

Also, the separation between components will obviously not be the same as called for in the actual mission.

To develop and validate the technology for LISA, a sequence of tests will be needed. Some aspects of the mission may not be testable on the ground. In these cases, one would attempt to develop appropriate models and validate them as well as possible on the test beds.

Relationship to Other Misions

LISA will be the pioneering mission for space detection of gravitational waves. As such many of the technology goals are specific to this unique mission, though some specific technology can be adapted from other missions.

The TRIAD mission, launched in 1972, is the only three-axis drag-free satellite flown. Many of the ideas for the LISA inertial sensor and spacecraft control are derived from engineering studies done for TRIAD. TRIAD demonstrated a disturbance reduction system based on capacitive sensing of a spherical test mass with long term acceleration noise of 5×10^{-11} m/s^2 or less. That disturbance reduction system was built jointly by Applied Physics Laboratory and Stanford University.

The Space Interferometer Mission (SIM) is developing a great deal of technology related to laser interferometry. SIM is designed to measure the angles between stars with micro-arcsecond resolution. This relies in part on being able to measure the distance between telescope elements separated by ~10 m with an accuracy of 1 nm. Some of the challenges of the SIM laser metrology are not relevant for LISA, such as frequent large changes in telescope pointing and spacecraft attitude and absolute length measurements. Also the SIM laser operate at lower power and longer wavelength than desired for LISA. However many of the components developed and tested by SIM can be used for LISA as well as the engineering experience in developing interferometers for space.

The Gravity Recovery and Climate Experiment (GRACE) has many similarities to the LISA mission. GRACE involves two spacecraft measuring changes in the distance between them to recover information about the Earth's gravity field. The two GRACE spacecraft will be in low polar orbits, with spacecraft separation of ~400 km. Each spacecraft will transmit a microwave signal with wavelength ~1 cm and receive a similar signal from the other spacecraft. The difference in carrier phase will be measured at each spacecraft and combined to form a one-arm microwave interferometer much like on of the LISA arms. Each spacecraft also carries and accelerometer to measure distance changes induced by atmospheric drag. These accelerometers are similar in design to candidate inertial sensors for LISA. The signal frequencies of interest for GRACE, which are related to the orbital period, are similar to those for LISA. GRACE will provide validation of inertial sensor performance for LISA at a reduced level of performance. Much of the GRACE phase measurement system can be adapted for use by LISA.

References

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